MULTIPLE-GEAR ANALYSIS FOR FLEXIBLE PAVEMENT DESIGN IN LEDFAA

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ABSTRACT

An analysis of the effects of interaction between individual wheel responses in multiple-gear configurations, including both the 16-wheel Boeing B-747 and the 20-wheel Airbus A380 main gears, was carried out using the Federal Aviation Administration's (FAA) LEDFAA design methodology. This analysis was partly motivated by the need to reconcile conflicting assumptions between the California Bearing Ratio (CBR)-based FAA and LEDFAA design procedures for multiple-gear aircraft. The original version of LEDFAA treated the B-747 as a dual-tandem aircraft for the purpose of computing the flexible strain response, involving the full 16-wheel assembly only for computing the pass-to-coverage ratio. As shown in this paper, this approach does not necessarily yield the maximum strain for design, but was justified in the original LEDFAA procedure since only the B-747 was affected, and the procedures were fully calibrated against CBR designs for mixes including the B-747. In conjunction with the upgrade to LEDFAA version 1.3, which includes the A380 in its aircraft library, a re-evaluation of LEDFAA design procedures for multiple-gear aircraft was required. The first step in this re-evaluation was to perform an analysis of multiple-gear strains for flexible pavements, using the LEAF computer program, to determine whether variations in computed subgrade strain due to various gear groupings have a potentially significant effect on flexible design thickness. A previous analysis by the FAA concerning rigid pavements concluded that such effects were not significant for rigid design.

Results presented herein for a range of design conditions verify that the effects of multiple-gear interaction are significant, especially for thicker pavements constructed on weaker subgrades. Comparisons with the CBR method of design are presented, using the FAA's COMFAA program to determine total thickness for various gear combinations.

INTRODUCTION

The Federal Aviation Administration's (FAA) LEDFAA pavement thickness design procedure, implemented as a Windows-based computer program, was introduced in 1995 as FAA Advisory Circular (AC) 150/5320-16. Although initially designated as the design standard for airport pavements intended to carry the triple-dual-tandem (TDT) Boeing B-777, the LEDFAA program is a valid procedure for all typical aircraft traffic mixes. Sensitivity studies conducted by the FAA [1] were used to calibrate the LEDFAA design procedures against the earlier FAA design procedures for a variety of narrow- and wide-body aircraft traffic mixes. Calibrations were against the California Bearing Ratio (CBR) method for flexible pavements and a Westergaard-based method for rigid pavements, both as implemented as complete design procedures in AC 150/5320-6C.

A comparison between LEDFAA and the CBR method of flexible pavement design must consider both the similarities and differences between the two procedures. While both methods account for the interactive effects of multiple wheels, the ways in which they do so are different. The CBR method makes use of the equivalent single-wheel load (ESWL) computation for multi-wheel aircraft gears, which implicitly treats the pavement structure as a uniform elastic half-space (Boussinesq model), but does not involve any strain calculations. Furthermore, the relationship between pavement thickness and design coverages for multiple-wheel aircraft is modified by the load repetition factor, also referred to as the alpha (α) factor, obtained from the analysis of full-scale tests. By contrast, the LEDFAA method considers the contribution of each wheel in the gear assembly to the combined strain at the top of the subgrade, as computed directly by layered elastic analysis (LEA). The LEDFAA approach eliminates both the alpha factor and the need for ESWL calculations. The LEDFAA failure model relates computed strains to failure coverages – again, based on full-scale test data.

The CBR-based design curves for flexible pavements in AC 150/5320-6D were developed using the ESWL for multiple-wheel gears. In general, the number of wheels used to compute ESWL is the number that yields the maximum value for ESWL. Therefore, the curves for the B-747, with four main gears consisting of four wheels each, were developed based on all 16 wheels, since this grouping produces the maximum ESWL. By contrast, the original version of LEDFAA computed strain for the B-747 based on a single four-wheel gear, in conformance with the procedure used for other aircraft, whereby strain is computed for a single gear. For the existing aircraft fleet including the B-747, these conflicting assumptions lead to inconsistencies when calibrating the LEDFAA model to CBR designs. These inconsistencies are not significant when comparing designs for complete mixes consisting of a wide range of aircraft types but can give significantly different results when comparing single aircraft or mixes where a single aircraft type predominates. For example, thickness designs done by the LEDFAA and CBR procedures might match quite well for a DC-10 aircraft, but may differ significantly for a B-747 aircraft. If the LEDFAA internal parameters are then adjusted to force the designs for the two design procedures to match for the B-747 aircraft, then the DC-10 designs will be different.

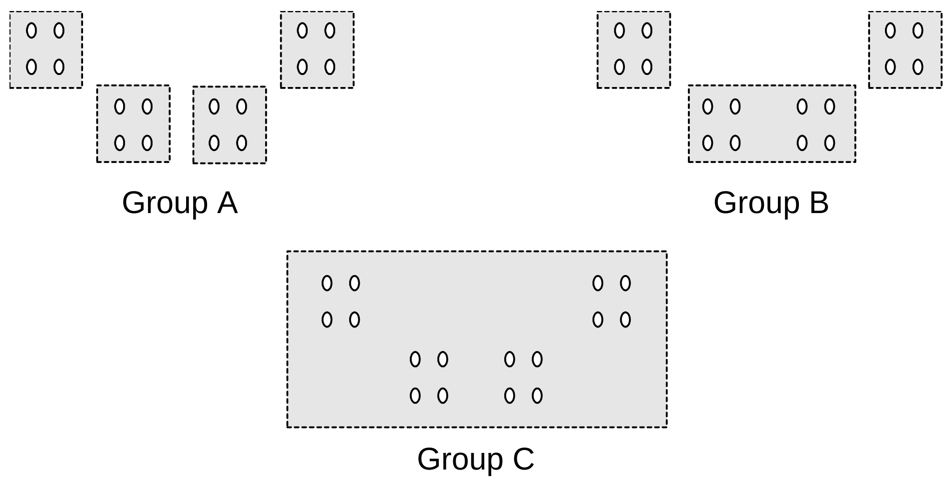
The issue of multiple-gear interaction has received new attention with the planned 2006 introduction of the Airbus A380 series. This aircraft will have a 20-wheel main gear assembly consisting of two four-wheel wing gears and two six-wheel body gears, with a gross weight up to 1.3 million pounds. An updated version of LEDFAA (version 1.3), including the A380 family in an expanded aircraft library, was released in May 2003. For LEDFAA 1.3, the flexible pavement strain computation procedure has been revised to reflect the maximum strain for a combination of gears. A major purpose of the research described herein was to evaluate the analytical strains produced by multiple-gear aircraft loads (A380 and B-747) on flexible pavements. A related goal was to identify the combination of gears giving the maximum strain for LEDFAA flexible pavement design. The implementation of the resulting strain computation procedure, as applied to A380 and B-747 aircraft, is described in reference [2].

ANALYSIS OF MULTIPLE-GEAR EFFECTS ON LEAF-COMPUTED STRAINS

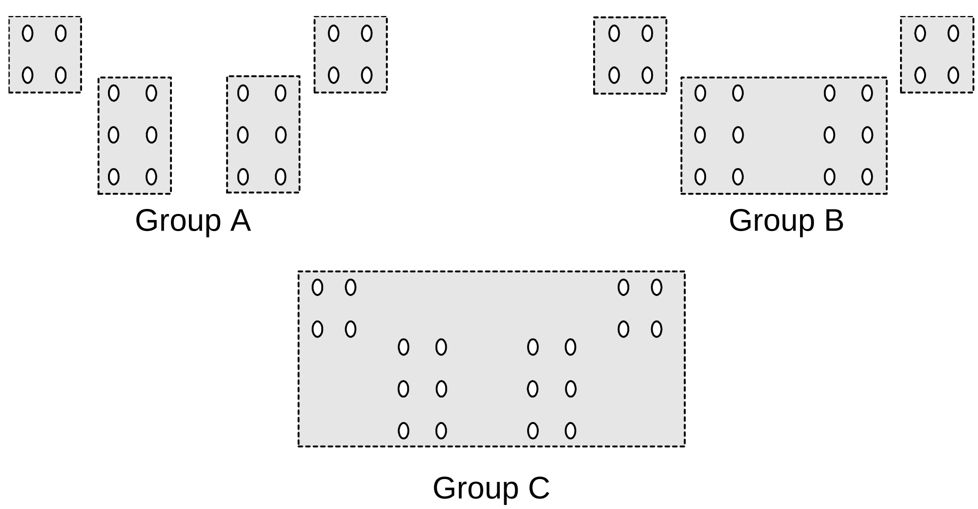
Table 1 lists the input data for an analysis of computed strain for three different groupings of the B-747 and the A380 main gear loads (figure 1). In Group 1, the strain is computed for each gear individually (i.e., any contribution from adjacent gears is neglected). In Group 2, the wing and body gears are considered separately, but the two body gears are treated as a unit. Group 3 consists of the entire main gear, including all 16 wheels of the B-747 and all 20 wheels of the A380. Group 1 corresponds to the strain computation implemented for the B-747 in LEDFAA 1.2. As indicated in table 1, three different subgrade strengths were assumed for the analysis, corresponding to CBR values of 3, 8, and 15. Since strains at the top of the subgrade were computed using the LEA-based LEAF program, CBR values for subgrade layers were converted to elastic modulus E for the analysis, using the relationship E = 1500 CBR (E in psi). Other layers were assigned the default material properties (E and Poisson’s ratio) from LEDFAA.

Table 1.
Input Data for Multiple-Gear Strain Analysis.

Layer	Structure 1 (CBR 3)	Structure 2 (CBR 8)	Structure 3 (CBR 15)
Surface Course, P-401	5 in.	5 in.	5 in.
Stab. Subbase, P-401	8 in.	8 in.	5 in.
Crushed Agg., P-209	design layer	design layer	design layer
Subgrade	infinite	infinite	infinite



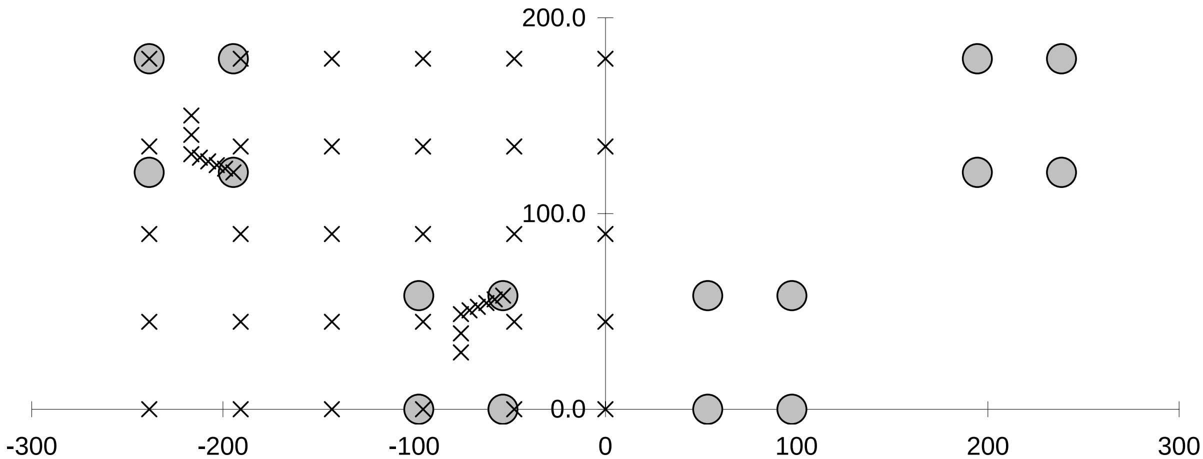
(a) B-747



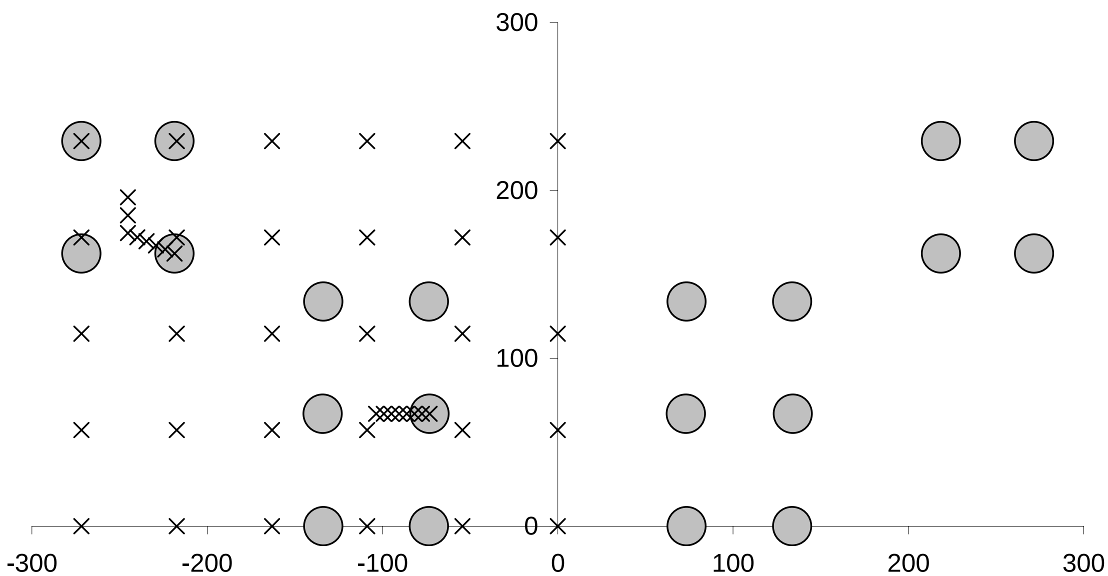
(b) A380

Figure 1. Gear Groupings for Multiple-Gear Analysis.

Table 2 summarizes the results of the analysis for all three groups. For groups A and B, maximum strains are reported separately for the wing gear and body gear loads. The group 3 strain is the maximum strain for all four gears, the location of which is not known a priori. Because the maximum strain may occur under a wing gear, body gear, or at some point in between, strains are computed at all the evaluation points shown in figure 2. The maximum strain over all the evaluation points in the array is taken as the maximum strain for the analysis. Figure 2 was constructed by superimposing a regular grid over the locus of evaluation points for the individual gears. While there is a possibility that the true maximum strain for a given layered elastic structure may occur a short distance away from the critical evaluation point in this array, the error is considered small enough to be neglected in practice.



(a) B-747



(b) A380

Figure 2. Evaluation points for LEAF strain analysis. (scale in inches)

Table 2.
LEAF Strain Comparison for Multiple-Gear Aircraft Loads
a. B-747-400 (Gross Weight = 873,000 lbs.)

Gear Grouping (Fig. 1)		Maximum vertical strain, top of subgrade (LEAF) Structure 1[a]	Structure 2[b]	Structure 3[c]
Group A	wing gear (4 wheel)	$9.768 \cdot 10^{-4}$	$1.173 \cdot 10^{-3}$	$1.181 \cdot 10^{-3}$
	body gear (4 wheel)	$9.768 \cdot 10^{-4}$	$1.173 \cdot 10^{-3}$	$1.181 \cdot 10^{-3}$
Group B	wing gear (4 wheel)	$9.768 \cdot 10^{-4}$	$1.173 \cdot 10^{-3}$	$1.181 \cdot 10^{-3}$
	body gear (8 wheel)	$1.105 \cdot 10^{-3}$	$1.157 \cdot 10^{-3}$	$1.169 \cdot 10^{-3}$
Group C	16 wheel	$1.178 \cdot 10^{-3}$	$1.153 \cdot 10^{-3}$	$1.170 \cdot 10^{-3}$

[a]LEDFAA 1.3 total design thickness for 1200 passes of B-747 = 60.05 in.
[b]LEDFAA 1.3 total design thickness for 1200 passes of B-747 = 28.13 in.
[c]LEDFAA 1.3 total design thickness for 1200 passes of B-747 = 19.65 in.

b. A380-800 (Gross Weight = 1,239,000 lbs.)

Gear Grouping (Fig. 1)		Maximum vertical strain, top of subgrade (LEAF) Structure 1[a]	Structure 2[b]	Structure 3[c]
Group A	wing gear (4 wheel)	$8.015 \cdot 10^{-4}$	$1.156 \cdot 10^{-3}$	$1.189 \cdot 10^{-3}$
	body gear (6 wheel)	$9.676 \cdot 10^{-4}$	$1.166 \cdot 10^{-3}$	$1.163 \cdot 10^{-3}$
Group B	wing gear (4 wheel)	$8.015 \cdot 10^{-4}$	$1.156 \cdot 10^{-3}$	$1.189 \cdot 10^{-3}$
	body gear (12 wheel)	$1.077 \cdot 10^{-3}$	$1.145 \cdot 10^{-3}$	$1.154 \cdot 10^{-3}$
Group C	20 wheel	$1.154 \cdot 10^{-3}$	$1.136 \cdot 10^{-3}$	$1.169 \cdot 10^{-3}$

[a]LEDFAA 1.3 total design thickness for 1200 passes of A380 = 68.99 in.
[b]LEDFAA 1.3 total design thickness for 1200 passes of A380 = 28.36 in.
[c]LEDFAA 1.3 total design thickness for 1200 passes of A380 = 20.60 in.

Table 2 shows that the strain contribution due to additional gears is most significant for weaker subgrades and thicker structures. For thinner structures on relatively strong subgrades, the contribution of the additional gear(s) may actually be negative, offsetting some of the strain caused by the single-gear load. A detailed analysis of this effect can be found in reference [3]. Based on results similar to those shown in table 2, the FAA has now revised LEDFAA for flexible pavement design to incorporate strains based on all gears of multiple-gear assemblies [2]. A previous analytical study conducted by the FAA [4] used three-dimensional finite element analysis to conclude that for rigid pavements, the influence of multiple gears on concrete slab stresses used for design was not significant.

In LEDFAA, the design thickness is the thickness of structure that gives a cumulative damage factor (CDF) equal to one for a given design life, generally 20 years. The CDF contribution of a given aircraft is influenced by two independent variables: (1) the coverage-to-pass (C/P) ratio, and (2) the number of coverages to failure, which is in turn a function of the computed strain. Thus, the additional gear can influence the design thickness in either of two ways, by changing the maximum computed strain (table 2) or by altering the C/P ratio. The relative effects of these two variables on the CDF calculation are illustrated in table 3 for structure 1 (CBR 3). From table 3, it is seen that the gear group has a much more significant effect on the computed strain than on the C/P ratio. Table 3 also shows that the LEDFAA 1.3 design thickness in table 2 is based on Group $\hat{C}$, that is, with strain computed using all wheels in the main gear assembly but with the pass-to-coverage ratio computed separately for the wing and body gears. The detailed implementation of this method in LEDFAA 1.3 is discussed in [2].

Table 3.
CDF Calculation Example (B-747-400, Gross Weight = 873,000 lbs., Structure 1).

Group	Gear	Strain, ε_v	Coverages to Failure, C_F	C/P Ratio[a]	CDF[b]
A	Wing	$9.768 \cdot 10^{-4}$	417844	2.725538E-03	0.0002
	Body (4 wheel)	$9.768 \cdot 10^{-4}$	417844	1.216338	0.0698
					0.0700
B	Wing	$9.768 \cdot 10^{-4}$	417844	2.725538E-03	0.0002
	Body (8 wheel)	$1.105 \cdot 10^{-3}$	72567	1.216338	0.4023
					0.4025
C	16 wheel	$1.178 \cdot 10^{-3}$	29101	1.217592	1.0042
$\hat{C}$	16 wheel (wing)	$1.045 \cdot 10^{-3}$	159589	2.725538E-03	0.0004
	16 wheel (body)	$1.178 \cdot 10^{-3}$	29101	1.216338	1.0031
					1.0035

[a]computed at critical offset

[b]based on 24000 passes; $\mathrm{CDF} = 24000 \times {(C/P)}/{C_F}$

COMPARISON WITH CBR METHOD OF THICKNESS DESIGN

Comparative design thicknesses for the sample structures in table 1 were computed based on the CBR method for a range of subgrade CBR values. Total pavement thicknesses for the CBR design were computed using the FAA's COMFAA computer program. All comparisons were based on 1,200 annual departures of the B-747, i.e., 24,000 total departures over a 20-year design life. Since the COMFAA program accepts coverages rather than passes as a direct input, it was necessary to convert passes to coverages using the pass-to-coverage (P/C) ratios referenced in AC 150/5320-6D [5]. Hence for the B-747, the number of design coverages for the CBR method is 24,000/1.85, or 12,973, where 1.85 is the specified P/C ratio for asphalt pavements. It should be noted that LEDFAA uses different P/C ratios than those specified in [5]. Comparisons are shown in tables 4 - 6. For the CBR designs, the gear groups correspond to the number of wheels used in computing the ESWL; e.g., for gear group C, all 16 wheels were used to compute the ESWL. Hence, gear group C is equivalent to using the FAA design charts in AC 150/5320-6D.

The three structures in table 1 include a stabilized subbase (P-401), in conformance with AC 150/5320-6D, which requires stabilized subbases for aircraft traffic in excess of 100,000 lbs. For CBR-based designs involving asphalt pavements on stabilized subbases, the total design thickness is determined by the choice of equivalency factors, which obviously depends on engineering judgment for a particular situation. For P-401 stabilized subbase and P-209 high-quality granular subbase, the acceptable equivalency factor ranges [5] are 1.2 - 1.6, and 1.2 - 1.8, respectively. For the present comparison, a mid-range equivalency factor of 1.4 was selected for both materials. Clearly, a higher equivalency factor could have been used, which would have resulted in lower total thicknesses for the CBR method.

Table 4.
LEDFAA vs. COMFAA Thickness Comparison for B-747 (Structure 1, CBR 3).

Group	LEDFAA Annual Passes	LEDFAA Coverages	AC 150/5320-6D Coverages[a]	Design Thickness, in. LEDFAA	COMFAA Conventional	COMFAA Stabilized[b]
A	1200	32,861	12,973	53.79	68.09	50.1
B	1200	30,996	12,973	56.96	73.44	53.9
C	1200	29,029	12,973	60.07	79.98	58.6

[a]P/C ratio = 1.85
[b]Assume 5 in. P-401 AC Surface, 1.4 equivalency factor for P-401 stabilized subbase, and P-209 subbase.

Table 5.
LEDFAA vs. COMFAA Thickness Comparison for B-747 (Structure 2, CBR 8).

Group	LEDFAA Annual Passes	LEDFAA Coverages	AC 150/5320-6D Coverages[a]	Design Thickness, in. LEDFAA	COMFAA Conventional	COMFAA Stabilized[b]
A	1200	39,958	12,973	28.70	33.34	25.2
B	1200	39,958[c]	12,973	28.70[c]	34.69	26.2
C	1200	45,787	12,973	28.15	36.72	27.7

[a]P/C ratio = 1.85
[b]Assume 5 in. P-401 AC Surface, 1.4 equivalency factor for P-401 stabilized subbase, and P-209 subbase.
[c]Wing gear controls.

Table 6.
LEDFAA vs. COMFAA Thickness Comparison for B-747 (Structure 3, CBR 15).

Group	LEDFAA Annual Passes	LEDFAA Coverages	AC 150/5320-6D Coverages[a]	Design Thickness, in. LEDFAA 1.3	COMFAA Conventional	COMFAA Stabilized[b]
A	1200	32,190	12,973	19.83	20.75	16.3
B	1200	32,190[c]	12,973	19.83[c]	21.32	16.7
C	1200	35,271	12,973	19.66	22.23	17.3

[a]P/C ratio = 1.85
[b]Assume 5 in. P-401 AC Surface, 1.4 equivalency factor for P-401 stabilized subbase, and P-209 subbase.
[c]Wing gear controls.

The comparisons in tables 4 - 6 show that the variation in total design thickness based on interaction between gears that would be obtained using the CBR-based design procedure is similar to the variation found in LEDFAA. Thus, for the thickest structures considered (CBR 3, table 4), the increase in total design thickness going from group A (single gear) to group C (all gears) is +6.3 inches for LEDFAA, compared to +8.5 inches for the CBR method. The total design thicknesses are also comparable, provided that LEDFAA designs are compared to CBR designs for gear group C (all gears considered). For the CBR 3 structure, the increase in thickness based on the vertical strain in the layered elastic method is significant but not as large as the corresponding increase in the CBR method. However, for the 8 and 15 CBR subgrade structures (structures 2 and 3), LEDFAA showed negligible differences in the design thickness between gear groups, whereas the CBR method still showed significant, though smaller, differences in design thickness. This result illustrates how the effects of reduced interaction, and possible negative strains, can cause layered elastic calculations to be somewhat less sensitive to multiple-gear groupings compared to ESWL calculations.

CONCLUSIONS

An analysis of multiple-gear subgrade strains was performed using the layered elastic analysis program LEAF. This study concluded that the contribution of additional gears to the maximum subgrade strain produced under a gear may be significant, particularly for deeper structures on weaker subgrade, where interaction between gears is greatest. It was also noted that the contribution of additional gears is not always additive in a layered elastic analysis. These findings are of particular significance for LEDFAA flexible pavement designs involving the Boeing B-747 and the Airbus A380 aircraft, both of which have main gear assemblies consisting of four gears, with potential for significant interaction among gears.

Flexible design comparisons between LEDFAA and the CBR method for the B-747 aircraft show that in both cases the number of gears included in the calculation of pavement response affects the total design thickness. The FAA’s CBR design procedure for the B-747 assumes that all gears contribute to the ESWL. Flexible designs using LEDFAA 1.3 for the B-747 and the A380 aircraft will assume that all gears contribute to the strain.

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